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ABSTRACT

This document gives a short history of the development of dual VLF time-transmission technique. The theory of time recovery from the relative phase of the dual-frequency transmission is presented. The transmission and receiving requirements for cycle identification and cycle ambiguity resolution are described. Finally, an experiment to test the capability of time transmission of the OMEGA system is proposed.

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INTRODUCTION

The possibility of using VLF signals for time transmissions became evident when the received signal phase was found extremely stable over long distances. Morgan and Baltzer, Fey and Looney, and Chi and Witt were among the first to pioneer (in the early 1960's) the use of a dual-frequency technique to transmit time on VLF carriers.

In 1965, NBS (with NASA/GSFC's support) had completed the modification of an experimental transmitter, WWVL, to transmit at 10-second alternations, the dual VLF carriers at 20.0 and 20.5 kHz. The radiated power was relatively low, approximately 2 kw. To reduce the frequency dispersion effect, the frequency separation was soon changed to 100 Hz at 19.9 and 20.0 kHz.

Between December 1966 and June 1968, NASA (with the cooperation of NBS and RMS Engineering, Incorporated, and others) conducted several field tests of time reception of WWVL transmissions, in its Space Tracking and Data-Acquisition Network (STADAN). Portable crystal clocks and a cesium-frequency standard were used during these trips to measure the propagation delays. Because of the requirements for phase control of the two signals at the transmitter and the phase stability of the receivers, it was soon found that the cycle number identified at each receiving station varied between ±2 cycles, and could vary by as many as five cycles in some remote sites. In the early 1960's, OMEGA stations at Hawaii and Forestport, New York, were used to conduct lane-resolution studies using 200-, 500-, 1000-, and 2000-Hz frequency separations. In the late 1960's, the dual-frequency time-transmission technique was tried in the OMEGA station, Forestport, and also in Europe. Results of studies made on these tests convinced the experimenters that the technique was, indeed, sound and feasible for implementation, if the instrumentation phase errors at the transmitters and in the receiver design is reduced sufficiently to allow positive cycle identification, leaving only propagation error predominant.

THEORY OF DUAL-FREQUENCY TIME TRANSMISSION

Let t_0 be the time of the emitted signals at the transmitter for F_1 and F_2 and t_r be the received time of the signals relative to a clock at a receiving site. Then

$$t_r - t_0 = T_p + \Delta t_c \tag{1a}$$

$$= t_p + \Delta t_p + \Delta t_c \tag{1b}$$

$$= t_p + \Delta t \tag{1c}$$

where T_p = total propagation delay

t_p = calculable propagation delay

Δt_p = propagation delay anomaly

Δt_c = clock difference

$\Delta t = \Delta t_p + \Delta t_c$

Equation (1a) can also be written

$$T_p + \Delta t_c = n\tau_a + \left(n_1 + \frac{\Delta\phi_1}{2\pi}\right)\tau_1 \tag{2a}$$

$$= n\tau_a + \left(n_2 + \frac{\Delta\phi_2}{2\pi}\right)\tau_2 \tag{2b}$$

where n, n_1, and n_2 are integers

$\tau_a = k\tau_b = \frac{k}{\Delta F}$, k being an integer

$$\tau_b = \frac{1}{\Delta F} = \frac{\tau_1\tau_2}{\tau_2 - \tau_1}$$

$$\Delta F = F_1 - F_2$$

$$\tau_1 = \frac{1}{F_1}$$

$$\tau_2 = \frac{1}{F_2}$$

$\Delta\phi_1$ = phase difference of F_1 relative to a local clock

$\Delta\phi_2$ = phase difference of F_2 relative to the same local clock

From equations (2a) and (2b), one gets

$$\frac{n_1 + \frac{\Delta\phi_1}{2\pi}}{n_2 + \frac{\Delta\phi_2}{2\pi}} = \frac{\tau_2}{\tau_1}$$

Subtracting 1 from both sides of the equation and multiplying by $\frac{1}{\tau_2}$, one gets

$$\frac{n_1 - n_2 + \frac{\Delta\phi_{12}}{2\pi}}{\left(n_2 + \frac{\Delta\phi_2}{2\pi}\right)\tau_2} = \frac{\tau_2 - \tau_1}{\tau_1 \tau_2} = \frac{1}{\tau_b} = \frac{k}{\tau_a} \tag{3}$$

where $\Delta\phi_{12} = \Delta\phi_1 - \Delta\phi_2$

Substituting equation (3) into equation (2b),

$$T_p + \Delta t_c = \left\{n + \frac{1}{k}\left[(n_1 - n_2) + \frac{\Delta\phi_{12}}{2\pi}\right]\right\}\tau_a \tag{4a}$$

$$= \left\{nk + \left[(n_1 - n_2) + \frac{\Delta\phi_{12}}{2\pi}\right]\right\}\tau_b \tag{4b}$$

Rearranging equation (4b), one gets

$$T_p + \Delta t_c - n\tau_a = \frac{n_1 - n_2 + \frac{\Delta\phi_{12}}{2\pi}}{\Delta F} \tag{4c}$$

From equation (4c), one can see that T_p and Δt_c are directly related to $\Delta\phi_{12}$ and inversely related to ΔF.

CYCLE IDENTIFICATION

Time is recovered from the identification of a particular cycle of a carrier signal and the relative phase difference between the received carrier signal and the local clock; therefore, it is important not only to know the cycle identification but also its relation as a function of time.

The cycle identification is achieved with the knowledge of the propagation path delay, T_p. This propagation delay can also be measured directly through the use of a portable clock.

Using equations (1), (2), and (4), one gets

$$n_1 = \frac{1}{\tau_1}(t_p - n\tau_a) + \left(\frac{\Delta t}{\tau_1} - \frac{\Delta\phi_1}{2\pi}\right) \tag{5a}$$

$$n_2 = \frac{1}{\tau_2}(t_p - n\tau_a) + \left(\frac{\Delta t}{\tau_2} - \frac{\Delta\phi_2}{2\pi}\right) \tag{5b}$$

$$n_1 - n_2 = k\left[\frac{1}{\tau_a}(t_p - n\tau_a) + \left(\frac{\Delta t}{\tau_a} - \frac{\Delta\phi_{12}}{2\pi k}\right)\right] \tag{5c}$$

$$= \frac{1}{\tau_b}(t_p - nk\tau_b) + \left(\frac{\Delta t}{\tau_b} - \frac{\Delta\phi_{12}}{2\pi}\right) \tag{5d}$$

The first terms in the right-hand side of equations (5) are constants and the second terms are time-dependent due to such factors as the instability of the propagation medium and the clocks.

Neither n_1 nor n_2 can be determined independently by equations (5a) and (5b) since $\Delta\phi_1$ and $\Delta\phi_2$ are time-dependent especially during sunrise and sunset hours and are also affected by the propagation disturbances. Additionally, the propagation time-delay anomaly, Δt_p, is not known and cannot be easily determined. For this reason, equation (5c) or (5d) is used. In these equations, the

relative phase difference of the two VLF signals at a receiving site is used in part to reduce the propagation effect on the signal phase of each received signal and to determine n_1 or n_2, based on some a priori knowledge of $n_1 - n_2$, especially if an estimate of the propagation delay time can be made.

AMBIGUITY RESOLUTION

Because of the sinusoidal nature of the time-transmission technique used in the dual VLF transmissions, some ambiguous periods cannot be resolved without additional transmission of coarse time or the use of other techniques to resolve the ambiguity time. For clarity, we define the beat period, τ_b, as $1/\Delta F$, i.e., the time at which the phase of the two signals at F_1 and F_2 are coincident. Then $\Delta F = F_1 - F_2$ is the beat frequency. The ambiguity period, τ_a, is defined as the time at which the phase of the two signals are not only coincident but also occurs at the positive-going zero-crossing of the sinusoidal signals as shown in Figure 1.

Let

$$\tau_a = k_1 \tau_1 = k_2 \tau_2 = k \tau_b = \frac{1}{Q} \tag{6a}$$

where k_1 is the integer number of cycles of F_1 in τ_a, k_2 is the integer number of cycles of F_2 in τ_a, k is the integer number of cycles of ΔF in τ_a, and Q, i.e.,

$$Q = \frac{F_1}{k_1} = \frac{F_2}{k_2} = \frac{\Delta F}{k} \tag{6b}$$

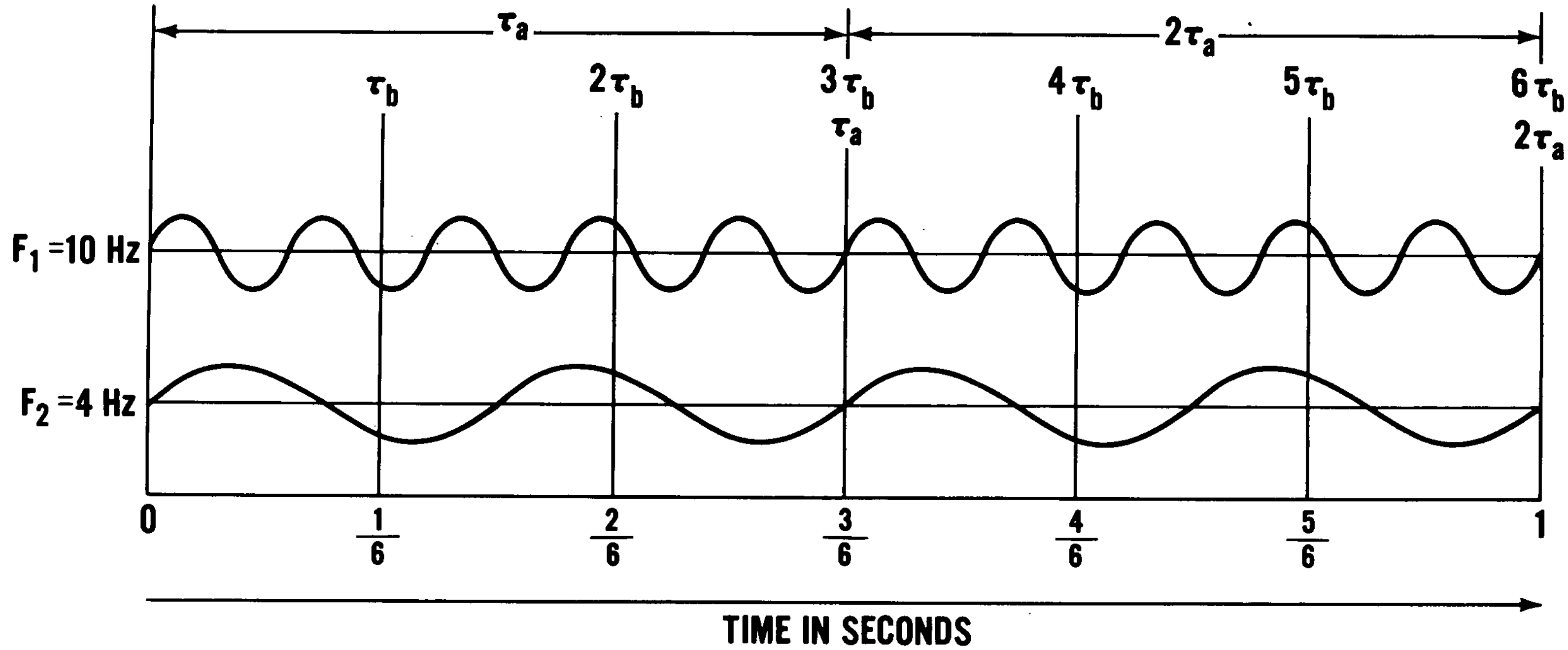
is the largest common divisor of F_1 and F_2.

Since

$$\frac{k_1}{k_2} = \frac{\tau_2}{\tau_1}$$

$$\left(\frac{k_1 - k_2}{k_2}\right) \frac{1}{\tau_2} = \left(\frac{\tau_2 - \tau_1}{\tau_1}\right) \frac{1}{\tau_2} = \frac{1}{\tau_b}$$

$$k_2 \tau_2 = (k_1 - k_2)\, \tau_b = k \tau_b \tag{6c}$$



$F_1 = 10$ Hz

$F_2 = 4$ Hz

$$Q = \frac{F_1}{k_1} = \frac{F_2}{k_2} = 2$$

$$k_1 = \frac{F_1}{Q} = 5$$

$$k_2 = \frac{F_2}{Q} = 2$$

$$k = k_1 - k_2 = 3$$

$$\tau_b = \frac{1}{\Delta F} = \frac{1}{6} \text{ sec}$$

$$\tau_a = k\,\tau_b = \frac{3}{6} \text{ sec}$$

Figure 1. Ambiguity Period and Beat Period for Cycle Identification in Dual VLF Time Transmissions

Therefore

$$k = k_1 - k_2 \tag{7a}$$

and

$$k_1 = \frac{F_1}{Q} \tag{7b}$$

$$k_2 = \frac{F_2}{Q} \tag{7c}$$

It should be mentioned here that the value of $(n_1 - n_2)$ in an ambiguity period takes 1, 2, ... k. For a fixed location, $(n_1 - n_2)$ does not change with time if the frequency dispersion effect due to the propagation medium is accounted for or is assumed to be small. This is also one reason for selecting a small frequency separation between the two VLF carriers.

CYCLE WELLS

This concept was developed, in 1966, for grouping the cycle numbers which cannot be uniquely determined from the dual VLF transmissions. Cycle variation can be observed at a receiving site when the relative phase or differential phase of the two emitted signals at the transmitter cannot be controlled to a constant value or zero; when the phase-difference measurement in a receiver is nonlinear for the dual frequencies due to variations of environmental conditions, signal amplitude, and antenna orientation; and when there are large ionospheric disturbances causing large propagation delay variations (anomalies). When the combined errors are larger than $1/2\,|\tau_2 - \tau_1|$, the cycle number can be in error by Δn, which is time-dependent.

$$\Delta n \quad \frac{\Sigma\,\delta\,(\Delta\,\phi)}{\frac{1}{2}\,|\tau_2 - \tau_1|}$$

where $\Sigma\delta(\Delta\phi)$ is the combined phase errors mentioned above.

To account for these variations, the cycle determination from equations (5) is quantized into cycle wells with a width (or diameter) equal to the relative phase difference of one cycle of propagation for each signal, i.e., $|\tau_2 - \tau_1|$, and a wall thickness equal to the sum of the propagation delay anomaly and the relative phase control of the two frequencies at the transmitter, as shown in Figure 2.

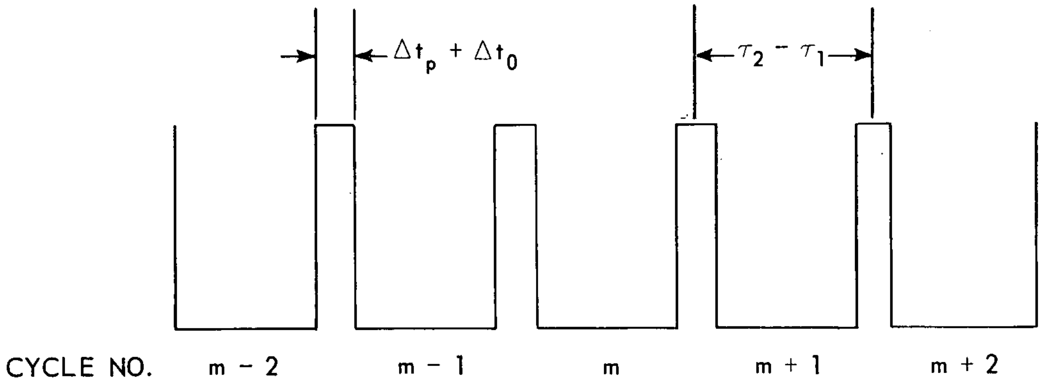


Figure 2. Cycle-Well Concept for Dual VLF Time Determination

TRANSMISSIONS AND RECEIVING REQUIREMENTS

Early in 1969, the U.S. Naval Observatory established an informal group, known as the OMEGA PTTI Advisory Group, to discuss details of the use of the OMEGA navigation system for the simultaneous dissemination of precise time.

This Group, after careful consideration of all aspects of the problems, made the recommendation which was accepted by the OMEGA project office in 1970. The recommendation was to implement the dual-frequency concept for time transmission in the OMEGA system. The frequency separation effect, which is 250 Hz, was selected for minimum frequency dispersion without placing too stringent phase-control requirements on the transmitters and receivers. The locations of the eight OMEGA stations, which form a global navigation system, are shown in Table 1. The dual frequencies proposed for each OMEGA station and the estimated date for beginning transmission are also given.

Figure 3 shows the 10-second OMEGA transmission sequence for the eight stations, labeled A to H. Three time segments are used for the transmission of navigation frequencies and the remaining five are reserved for time transmission and for transmission of intrasystem control data. The three segments labeled F_1 or F_2 (F_1/F_2) together with the two designated time segments for F_1 and F_2 form a coding format which can be used to transmit information at low rate. The present plan calls for 60 percent of the time to transmit intrasystem control data. The remaining 40 percent is still available for potential users to transmit other data.

Table 2 gives the pertinent data for cycle identification and ambiguity resolution for the OMEGA time-transmission frequencies. The last column in Table 2 gives

Table 1

OMEGA Station Locations and Proposed Dual Frequencies for Time Transmission and Intrasystem Data Communications

STATION	STATION DESIGNATION	COORDINATES**		FREQUENCIES F_1/F_2* (KHz)	EST. COMPL. DATES
		LATITUDE	LONGITUDE		
HAWAII	C	21°24'20.67"N	157°49'47.75"W	11.55, 11.80	10 NOV 72
TRINIDAD	B	10°42'06.20"N	61°38'20.30"W	12.00, 12.25	73
LA REUNION	E	≈ 16°S	56°E	12.05, 12.30	73
NORWAY	A	66°25'15.00"N	13°9'10.00"E	12.10, 12.35	73
AUSTRALIA	G	SOUTHEASTERN REGION		12.75, 13.00	74
JAPAN (Tsushima Is.)	H	≈ 34°38'N	129°26'E	12.80, 13.05	73
N. DAKOTA	D	46°21'57.20"N	98°20'08.77"W	12.85, 13.10	1 APR 72
ARGENTINA	F	43°03'12.38"S	65°11'28.50"W	12.90, 13.15	73

*F_1 is the frequency, which is an integer multiple of 100 Hz, and F_2 is an integer multiple of 50 Hz.

**Mercury data.

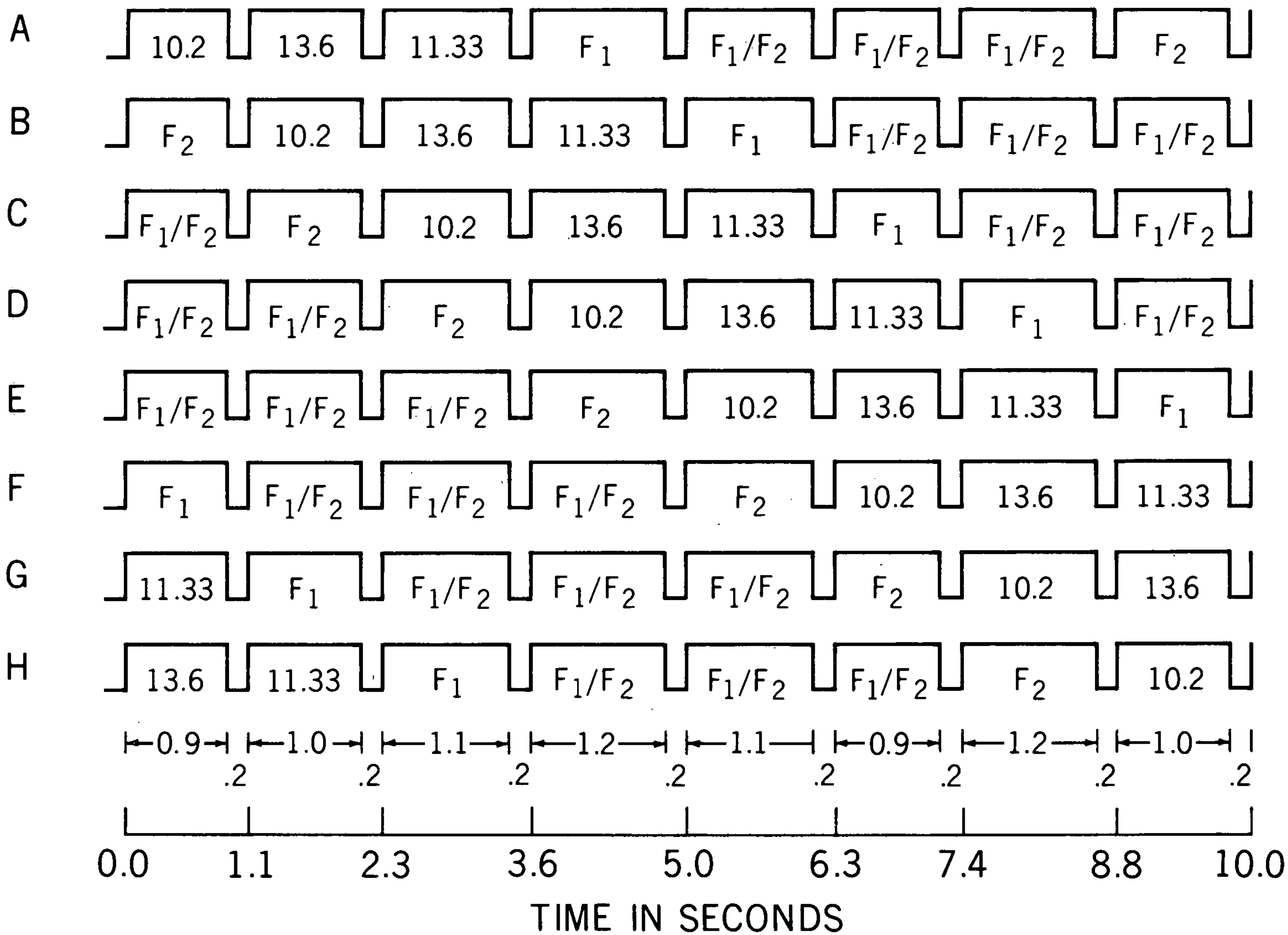


Figure 3. 10-Second OMEGA Transmission Sequence for Stations A Through H

Table 2

Pertinent Data for Cycle Identification and Ambiguity Resolution
for the OMEGA Time-Transmission Frequencies

STATION	F_1	F_2	k_1	k_2	k*	τ_a ms	τ_1 (μs)	τ_2 (μs)	$1/2 \lvert \tau_2 - \tau_1 \rvert$ (μs)
A	12.100	12.350	242	247	$\lvert -5 \rvert$	20	82.64	80.97	0.84
B	12.000	12.250	48	49	$\lvert -1 \rvert$	4	83.33	81.63	0.85
C	11.800	11.550	236	231	5	20	84.74	86.58	0.91
D	13.100	12.850	262	257	5	20	76.33	77.82	0.74
E	12.300	12.050	246	241	5	20	81.30	82.98	0.84
F	12.900	13.150	258	263	$\lvert -5 \rvert$	20	77.51	76.04	0.74
G	13.000	12.750	260	255	5	20	76.92	78.43	0.75
H	12.800	13.050	256	261	$\lvert -5 \rvert$	20	78.12	76.62	0.75

*The negative value of $k = k_1 - k_2$ results if $\Delta F = F_1 - F_2 < 0$.

the value of $1/2|\tau_2 - \tau_1|$. These data are important for cycle determination since an error of one cycle results if the combined errors (in phase control at the transmitter, the propagation delay due to medium, and phase stability and resolution in the receiver) exceed $1/2|\tau_2 - \tau_1|$.

The phase of the dual frequencies for time transmissions relative to a second tick at each of the eight potential OMEGA stations will be held within 0.1 μs. The instrumentation phase error of the OMEGA time receiver under normal operating conditions will be less than 0.2 μs. Using a simple arithmetic sum, the total phase instabilities contributed by the transmitter and the receiver is one-third of the required phase stability, $1/2|\tau_2 - \tau_1|$, for positive cycle identification. If propagation delay anomaly does not exceed two-thirds of the required phase stability, i.e., about 0.5 μs, then the cycle identification on a carrier frequency of the OMEGA system can be uniquely determined. The resolution of the received time, under typical conditions, should be the phase stability of a single VLF carrier, i.e., 1 to 2 microseconds. The OMEGA station epoch, as a goal, is to be maintained within ±2.5 μs relative to the January 1972 UTC scale.

A PROPOSAL: "TO TEST THE CAPABILITY OF THE OMEGA TIME-TRANSMISSION SYSTEM"

The Naval Electronics Laboratory Center, under NASA support, is currently developing an OMEGA timing receiver. The receiver is designed especially to reduce problems associated with positive cycle determination. The construction of the receiver is expected to be completed by April 1972. Those activities who are interested in precise time synchronization on a world-wide basis are invited to participate in the experiment or a field test to determine the capability of the OMEGA time-transmission system. It is hoped that enough receivers can be procured for placement at various locations such as one-half, one, one and one-half, and two times the average distance between two OMEGA stations. Those who are interested in the participation of this test should contact Dr. Winkler, U. S. Naval Observatory, or the authors of this paper.

BIBLIOGRAPHY

1. Best, V. E.; Ratcliffe, J. A.; and Wilkes, M. V.; "Experimental Investigation of Very Long Waves Reflected from the Ionosphere," Proc. Roy. Soc. A156, 614, 1936.

2. Bracewell, R. N.; "The Ionospheric Propagation of Radio Waves of Frequency 16 kc/s Over Distances of About 200 km," Proc. IEE, IV 99, 219, 1952.

3. Pierce, J. A.; "The Diurnal Carrier Phase Variations of a 16 kc/s Transatlantic Signal," Proc. IRE, 43, 584-588, 1955.

4. Pierce, J. A.; "Intercontinental Frequency Comparison by Very Low Frequency Radio Transmissions," Proc. IRE, 45, 798-803, 1957.

5. Chilton, C. J.; Crombie, D. D., and Jean, A. G.; "Phase Variations in VLF Propagation," Chapter 19, Propagation of Radio Waves at Frequencies Below 300 Kilocycles AGAR Dograph 74, Pergamon Press.

6. Pierce, J. A.; Winkler, G. M. R.; and Corke, R. L.; "The 'GBR Experiment': A Trans-Atlantic Frequency Comparison between Cesium-Controlled Oscillators," Nature, Vol. 187, No. 4741, 914-916, September 1960.

7. Chilton, C. J.; Diede, A. H.; and Radicella, S. M.; "Transequatorial Reception of a Very-Low-Frequency Transmission," J. Geophys. Res. Vol. 69, No. 7, 1319-1327, April 1964.

8. Looney, C. H., Jr.; "VLF Utilization at NASA Satellite Tracking Stations," Radio Science, Vol. 68D, No. 1, 43-45, January 1964.

9. Brady, A. H.; Crombie, D. D.; Jean, A. G.; Murphy, A. C.; and Steele, F. K.; "Long-Lived Effects in the D-Region After the High-Altitude Nuclear Explosion of July 9, 1962,: J. Geophys. Res., Vol. 69, No. 9, 1921-1924, May 1964.

10. Walker, D., "Phase Steps and Amplitude Fading of VLF Signals at Dawn and Dusk," Radio Science, Vol 69D, No. 11, 1435-1443, November 1965.

11. Kaufmann, P.; and Schaal, R. E.; "The Effect of a Total Eclipse on Long Path VLF Transmission," J. Atom. & Terres. Phys., Vol. 30, 469-471, 1968.

12. Snyder, F. P. and Bickel, J. E., "Measured Amplitude Variations of the 19.8 kHz Field of NPM Near its Antipole," Radio Science, Vol. 2, No. 7, July 1967.

13. Gerard, V. B., "Anomalous Phase Variations GBR as Received in New Zealand," J. Atom & Terres. Phys. Vol. 28, 425-428, 1966.

14. Baker, D. M. and Davies, K.; "Solar Flare Effects and the Relaxation Time of the Ionosphere," J. Geophys. Res., Vol. 71, No. 11, 2840-2842, June 1966.

15. Reder, F.; Meara, L.; and De Laitre, L.; "Interfering VLF Radio Signals Observed on GBR-16.0 KC/s Transmissions During November and December 1965," Nature, Vol. 213, No. 5076, 5841585, February 1967.

16. Kaufmann, P. and Mendes, A. M., "Relative Changes on Lower Ionosphere Conductivity Gradients During SID Events," J. Geophys. Res., Vol. 73, No. 7, 2487-2493, April 1968.

17. Westerlund, S.; Reder, F. H.; and Abom, C.; "Effects of Polar Cap Absorption Events on VLF Transmissions," Planet Space Sci., Vol. 17, 1329-1374, 1969.

18. Morgan, A. H., "A New Method of Time Signal Modulation and Demodulation of VLF Carriers," NBS Report 7286, July 1962.

19. Morgan, A. H., and Baltzer, O. J., "A VLF Timing Experiment," Radio Science, Vol. 68D, No. 11, 1219-1222, November 1964.

20. Chi, A. R. and Witt, S. N., "Time Synchronization of Remote Clocks Using Dual VLF Transmissions," Proc. 20th Annual Symposium on Frequency Control, 588-611, April 1966.

21. Fey, L. and Looney, C. H., Jr., "A Dual Frequency VLF Timing System," IEEE Trans. Instrumentation and Measurement, Vol IM-15, No. 4, 190-195, December 1966.

22. Kane, J., "Travel Time and Phase Shift," J. Geophys. Res., Vol. 70, No. 8, 1893-1895, April 1965.

23. Crombie, D. D., "The Effect of Waveguide Dispersion on VLF Timing Systems," IEEE Trans. Antenna and Propagation, Vol. AP-15, No. 2, 322-323, March 1967.

24. Pierce, J. A., "OMEGA," IEEE Trans. Aerospace and Electronics Systems, AES-1, 3, 206-215, December 1965.

25. Swanson, E. R. and Tibbals, M. L., "The OMEGA Navigation System," Navigation, Vol. 12, No. 1, 24-35, 1965.

26. Palmer, W., "The OMEGA Navigation System as a Source of Frequency and Time," Proc. 24th Annual Symposium on Frequency Control, 345-360, 1970.

27. Swanson, E. R., "OMEGA VLF Timing," Proc. 25th Annual Symposium on Frequency Control, 159-166, 1971.

28. Fey, L. "Time Dissemination Capabilities, Using the OMEGA System," Proc. Annual Symposium on Frequency Control, 167-170, 1971.

29. Baltzer, O. J., "Microsecond Timekeeping by Means of Multiple Frequency VLF Reception," Electronic Inst. Digest, Vol. 6, No. 12, 75, December, 1970.

30. Swanson, E. R. and Kugel, C. P., "OMEGA VLF Timing," Naval Electronics Laboratory Center, NELC/TR 1740, November 1970.

31. Swanson, E. R. and Kugel, C. P.; "OMEGA Synchronization and Control." Naval Electronics Laboratory Center, NELC/TR 1757, March 1971.

32. Chi, A. R. and Fosque, H. S., "Changes in Standard Frequency and Time Signal Broadcasts," January 1, 1972.*

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